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Current Passing Through Grounding System of High Voltage Transformer Substation and Parameters Impacting on It When Lightning Strikes on the Grounding Wire of Transmission Line

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(Abstract) Current injecting a grounding system of high voltage transformer substation decides the amplitude and the voltage distribution along the grounding grid [1]-[2]. Therefore, the determination of short circuit current at substation is always cared by the designers. [9] suggested a new method to calculate the current passing through grounding system of high voltage substation when lightning strikes on the grounding wire of transmission line regardless of the impacting parameters. This paper studied clearly the influence of above parameters and from this, some interesting results were received.

Keywords: Grounding System; High Voltage Transformer Substation; Grounding Wire.

1. INTRODUCTION

This paper presents some new formulas to calculate the current passing through grounding system of high voltage substation and its dangerous zone when lightning strikes on the grounding wire of transmission line.

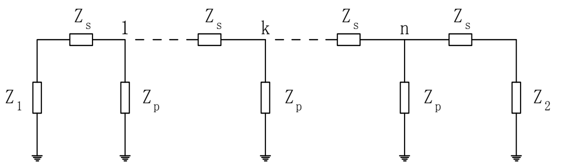


Fig .1 Equivalent circuit of grounding wire line

Based on transmission line models [3]-[5], the grounding wire system can be modeled as equivalent circuit (Fig.1). Where, n is the number of span, each span is represented by a pi-circuit. The shunt impedance Zp is the grounding impedance of electric pole and the series impedance Zs is the impedance of grounding wire of each span (if the transmission line has two grounding wires then this series impedance will be $Z_s/2$). Z_1 is the impedance of grounding system of the first substation and Z_2 is the impedance of grounding system of the second substation. In case of open-ended grounding wire line, $Z_2=\infty$. The system of grounding wire and impedance of electric pole can be modeled as a series of connected n pi-elements equivalent circuit with lumped Zs-Zp. So, the calculation of lightning current will be a process to solve this n pi-elements equivalent circuit.

2. CALCULATING THEORY

2.1 Impedances

From [6]-[7], in case of open-ended grounding wire line, we get the Thevenin impedance (seeing from the position that lightning strikes to the end of the grounding wire line) as follows:

$$Z_{th0}=\frac{\alpha_1\left(b-\sqrt{4Z_sZ_p+Z_s^2}\right)^n-\alpha_2\left(b+\sqrt{4Z_sZ_p+Z_s^2}\right)^n}{\left(b+\sqrt{4Z_sZ_p+Z_s^2}\right)^n-\left(b-\sqrt{4Z_sZ_p+Z_s^2}\right)^n} \qquad (1)$$

where:

$$b=2Z_p+Z_s$$

$$\alpha_1=\frac{-Z_s+\sqrt{4Z_sZ_p+Z_s^2}}{2}$$

$$\alpha_2=\frac{-Z_s-\sqrt{4Z_sZ_p+Z_s^2}}{2} \text{ or } \alpha_2=-\left(Z_s+\alpha_1\right)$$

In case of the end of the grounding wire line connecting with the grounding system impedance (Z_1), [8], [9] we get the Thevenin impedance as follows (see Appendix):

$$Z_{th1}=Z_{th0}-\frac{Z_{pTD}^2}{Z_{th0}+Z_1}. \qquad (2)$$

where:

$$Z_{pTD}=\frac{2^nZ_p^n\sqrt{4Z_sZ_p+Z_s^2}}{\left(b+\sqrt{4Z_sZ_p+Z_s^2}\right)^n-\left(b-\sqrt{4Z_sZ_p+Z_s^2}\right)^n} \qquad (3)$$

2.2 Calculation of currents

We consider two cases (Fig. 1):
Case one: When lightning strikes at the gate pole of the first substation, we have the following equivalent circuit:

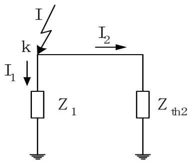


Fig .2 Equivalent circuit

Current passing through grounding system of substation 1 (Fig. 2) is calculated as follows:

$$I_{z1} = \frac{Z_{th2}}{Z_1 + Z_{th2}} I \qquad (4)$$

where Z_{th2} is the Thevenin impedance of the grounding wire of transmission line (seeing from the position that lightning strikes to the second substation) (Ω). Z_1 is the grounding system impedance of first substation (Ω). I is the lightning current value (kA).

Case two: When lightning strikes at the k^{th} electric pole on the grounding wire of transmission line.

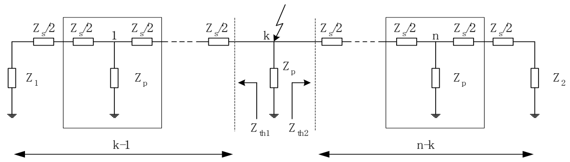


Fig .3 Equivalent circuit model

We alter the circuit in (Fig.3) for (Fig.4).

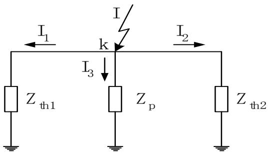


Fig. 4 Equivalent Thevenin circuit

Then, current passing through grounding system of substation (Fig.4) is calculated as follows:

$$\begin{cases} I_1 = \dfrac{Z_{th2} Z_p}{Z_p Z_{th1} + Z_{th2} Z_p + Z_{th1} Z_{th2}} I & (5) \\ I_2 = \dfrac{Z_{th1} Z_p}{Z_p Z_{th2} + Z_{th1} Z_p + Z_{th1} Z_{th2}} I & (6) \\ I_3 = \dfrac{Z_{th1} Z_{th2}}{Z_p Z_{th2} + Z_{th1} Z_p + Z_{th1} Z_{th2}} I & (7) \end{cases}$$

where Z_{th1} is the Thevenin impedance of the grounding wire of transmission line (seeing from the position that lightning strikes to the first substation) (Ω). Z_p is the shunt impedance at electric pole that lightning stroke (Ω).
We consider T -circuit equivalent impedance (seeing from the position that lightning strikes to the second substation) (Fig .3).

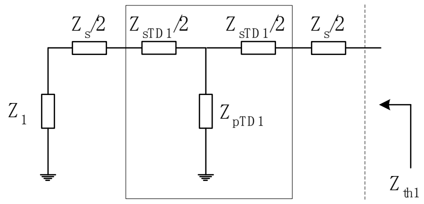


Fig .5 Equivalent circuit model to the left of the position that lightning strikes

Current passes through grounding system of first substation as follows:

$$I_{z1} = \frac{Z_{pTD1}}{Z_1 + Z_{th01}} I_1 \qquad (8)$$

where Z_{pTD1} is the elementary impedance of T -equivalent circuit to the left of the position that lightning strikes (Ω) (Fig.5). Z_{th01} is the Thevenin impedance of the grounding wire of transmission line (seeing from the position that lightning strikes to the first substation) in case of open-ended grounding wire line at this substation (Ω).
Similar calculation:

$$I_{z2} = \frac{Z_{pTD2}}{Z_2 + Z_{th02}} I_2 \qquad (9)$$

where Z_{pTD2} is the elementary impedance of T -circuit equivalent to the right of the position that lightning strikes (Ω). Z_{th02} is the Thevenin impedance of the grounding wire of transmission line (seeing from the position that lightning strikes to the second substation) in case of open-ended grounding wire line at this substation (Ω). Z_2 is the grounding system impedance of second substation (Ω).
Substituting the above formulas (8), (9) into equations (5), (6) we obtain:

$$\begin{cases} I_{z1} = \dfrac{Z_{pTD1} Z_{th2}}{Z_1 + Z_{th01}} \times \dfrac{Z_p}{Z_p Z_{th2} + Z_{th1} Z_p + Z_{th1} Z_{th2}} I \\ I_{z2} = \dfrac{Z_{pTD2} Z_{th1}}{Z_2 + Z_{th02}} \times \dfrac{Z_p}{Z_p Z_{th2} + Z_{th1} Z_p + Z_{th1} Z_{th2}} I \end{cases} \qquad (10)$$

2.3 Summary

From the above analysis, we have a method to calculate the current value passing through the grounding system impedance of substation when lightning strikes at any point on the grounding wire of transmission line as follows:
(i). We determine the Thevenin impedance (seeing from the position that lightning strikes to the substations) in case of open-ended grounding wire line at the substations, with the number of nodal point is $(k-1)$ and $(n-k)$ as follows:

$$\begin{cases} Z_{th01} = \dfrac{\alpha_1\left(b - \sqrt{4Z_s Z_p + Z_s^2}\right)^{k-1} - \alpha_2\left(b + \sqrt{4Z_s Z_p + Z_s^2}\right)^{k-1}}{\left(b + \sqrt{4Z_s Z_p + Z_s^2}\right)^{k-1} - \left(b - \sqrt{4Z_s Z_p + Z_s^2}\right)^{k-1}} \\ Z_{th02} = \dfrac{\alpha_1\left(b - \sqrt{4Z_s Z_p + Z_s^2}\right)^{n-k} - \alpha_2\left(b + \sqrt{4Z_s Z_p + Z_s^2}\right)^{n-k}}{\left(b + \sqrt{Z_s Z_p + Z_s^2}\right)^{n-k} - \left(b - \sqrt{4Z_s Z_p + Z_s^2}\right)^{n-k}} \end{cases} \qquad (11)$$

where α_1, α_2 and b was considered in formula (1).

(ii). Determine the Thevenin impedance (seeing from the position that lightning strikes to the substations) in case of

Lightning position	%I R_p=5	%I R_p=10	%I R_p=15	%I R_p=20	%I R_p=25	%I R_p=30	%I R_p=35	%I R_p=40
0	78.7	82.8	85.1	86.6	87.	88.5	89.2	89.7
1	45.2	55.8	61.6	65.4	68.2	70.4	72.	73.6
2	25.9	37.6	44.6	49.4	53.1	56.0	58.3	60.3
3	14.9	25.3	32.2	37.3	41.3	44.5	47.2	49.5
4	8.55	17.0	23.3	28.2	32.1	35.4	38.1	40.5
5	4.91	11.5	16.9	21.3	25.0	28.1	30.8	33.2
6	2.81	7.75	12.2	16.1	19.4	22.	24.9	27.2
7	1.61	5.22	8.86	12.1	15.1	17.8	20.2	22.3
8	0.92	3.51	6.41	9.20	11.7	14.1	16.3	18.3
9	0.53	2.37	4.64	6.95	9.18	11.	13.2	15.0

grounding wire line connecting with grounding system of these substations, with the number of nodal point is $(k-1)$ and $(n-k)$ as follows:

$$\begin{cases} Z_{th1} = Z_{th01} - \dfrac{Z_{pTD1}^2}{Z_{th01} + Z_1} \\ Z_{th2} = Z_{th02} - \dfrac{Z_{pTD2}^2}{Z_{th02} + Z_1} \end{cases} \qquad (12)$$

where Z_{pTD1}, Z_{pTD2} have form as formula (3)

(iii). The current which passes through the grounding system impedance of substations when lightning strikes at any point on the grounding wire of transmission line is calculated as follows:

$$\begin{cases} I_{z1}(k) = \dfrac{Z_{pTD1}}{Z_1 + Z_{th01}} \times \dfrac{Z_p}{Z_p Z_{th2} + Z_{th1} Z_p + Z_{th1} Z_{th2}} \times Z_{th2} I \\ I_{z2}(k) = \dfrac{Z_{pTD2}}{Z_2 + Z_{th02}} \times \dfrac{Z_p}{Z_p Z_{th2} + Z_{th1} Z_p + Z_{th1} Z_{th2}} \times Z_{th1} I \end{cases} \qquad (13)$$

where $Z_{th01}, Z_{th02}, Z_{th1}, Z_{th2}, Z_{pTD1}, Z_{pTD2}$ was considered in above formulas.

3. APPLICATION

1. Current passing the grounding system of substation with impact of R_p:

a). R_p is constant.

Surveying the following parameters:

Grounding resistance of electric pole changes from 5 to 40(Ω),

Grounding resistance of substation 1: $R_1 = 1(\Omega)$.

Grounding wire ПС-25: $R_s = 6.32(\Omega/km)$.

Number of span: n=50.

Results received as follows:

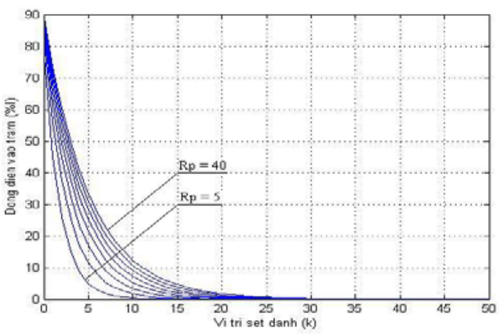


Fig.6: Graph of Current (%) passing the grounding system of substation 1 in term of lightning position k.

Table T1: Current (%) passing through grounding system of substation 1 in terms of lightning position k

From Fig.6 (and from Table T1), with a given lightning current I, we have:

-The more the grounding resistance of the electric pole is, the higher the current passes through grounding system of substation.

-The more the grounding resistance of the electric pole is, the larger the dangerous zone for substation is.

-We can clearly determine the lightning position that creates a risk to substation.

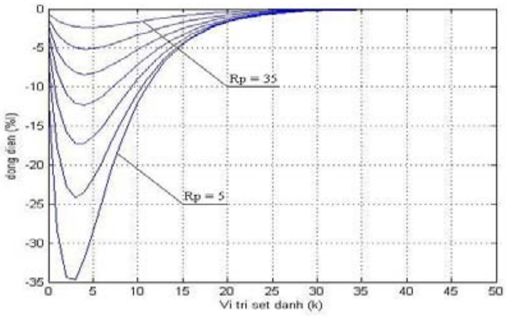


Fig.7: (%) of current at grounding system of substation in terms of lightning position k

Table T2: (%) of current at grounding system of substation in terms of lightning position k

Lightning position	(%I) (R_p=5)	(%I) (R_p=10)	(%I) (R_p=15)	(%I) (R_p=20)	(%I) (R_p=25)	(%I) (R_p=30)	(%I) (R_p=35)
0	-11.0	-6.8	-4.65	-3.16	-2.08	-1.24	-0.56
1	-28.3	-17.7	-11.9	-8.17	-5.37	-3.20	-1.45
2	-34.4	-22.7	-15.7	-10.9	-7.25	-4.36	-1.99
3	-34.6	-24.1	-17.2	-12.	-8.17	-4.96	-2.28
4	-32.0	-23.5	-17.2	-12.3	-8.42	-5.16	-2.39
5	-28.3	-21.7	-16.3	-11.9	-8.25	-5.11	-2.39
6	-24.4	-19.54	-15.05	-11.17	-7.81	-4.88	-2.30
7	-20.7	-17.16	-13.51	-10.19	-7.22	-4.56	-2.16
8	-17.4	-14.8	-11.9	-9.14	-6.55	-4.18	-2.00
9	-14.5	-12.6	-10.4	-8.09	-5.87	-3.77	-1.82
10	-12.03	-10.7	-8.98	-7.08	-5.19	-3.37	-1.64
11	-9.94	-9.04	-7.68	-6.14	-4.56	-2.99	-1.46
12	-8.19	-7.57	-6.53	-5.29	-3.97	-2.62	-1.29
13	-6.74	-6.31	-5.53	-4.53	-3.43	-2.29	-1.14
14	-5.54	-5.25	-4.65	-3.86	-2.96	-1.99	-0.99

Surveying the current through grounding system of substation (see Fig.7 and Table T2), we obtained: the faster the current decreases, the smaller the grounding resistance of electric pole is.

b). Changing R_p of electric pole close to substation

Surveying the following parameters:

Fixing grounding resistance of electric pole from 10 to 40(Ω), only changing grounding resistance of electric pole close to substation

Grounding resistance of substation 1: $R_1 = 1(\Omega)$.

Grounding wire ПС-25: $R_s = 6.32(\Omega/km)$.

Number of span: n=50.

Results received as follows:

Surveying at first electric pole with $R_p = 5(\Omega)$

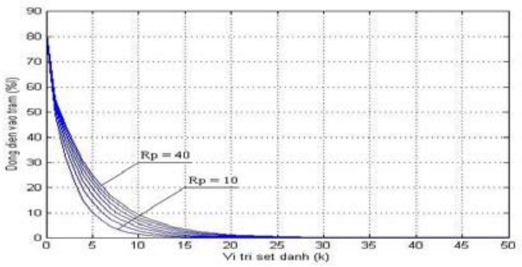


Fig.8: Graph of Current (%) passing the grounding system of substation 1 in term of lightning position k with resistance of first electric pole 5Ω.

Surveying at first 2 electric poles with $R_p = 5(\Omega)$

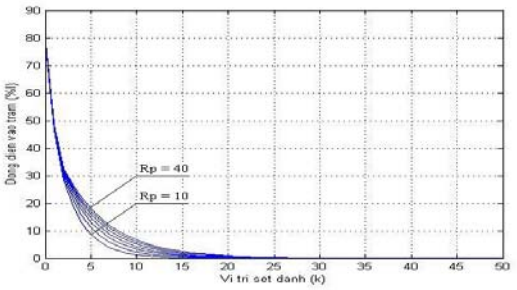


Fig.9: Graph of Current (%) passing the grounding system of substation 1 in term of lightning position k with resistances of first 2 electric poles 5Ω.

Surveying **at first 3 electric poles with $R_p = 5(\Omega)$**

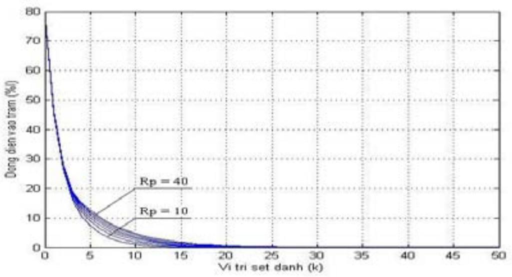


Fig.10: Graph of Current (%) passing the grounding system of substation 1 in term of lightning position with resistance of first 3 electric poles 5Ω.

Comparing the values of current passing grounding system of substation 1 in Fig. 6, 8, 9 and 10 we saw that: this current fast decreases (decreasing dangerous zone) and only in some spans it will goes out of the dangerous zone.

2. Current passing the grounding system of substation with impact of R_s:

Surveying the following parameters:

Changing grounding wire: ПС-25: $R_s = 6.32(\Omega/km)$, ПС-35: $R_s = 4.47(\Omega/km)$, ПС-50: $R_s = 3.45(\Omega/km)$, ПС-70: $R_s = 2.19(\Omega/km)$, ПС-95: $R_s = 1.88(\Omega/km)$.

Grounding resistance of substation 1: $R_1 = 1(\Omega)$.

Grounding resistance of electric pole: $R_p = 5(\Omega)$.

Number of span: n=50.

Results received as follows:

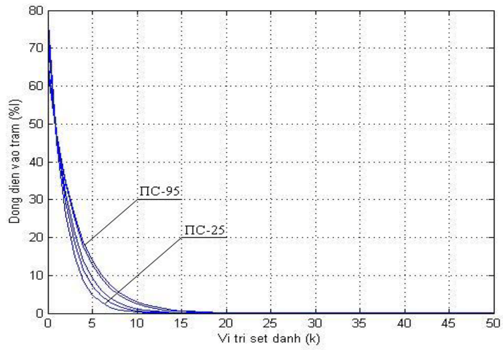


Fig.11: Graph of Current (%) passing the grounding system of substation 1in term of lightning position k.

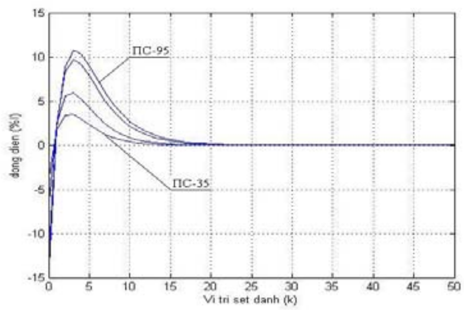
From Fig.11 (and from Table T3) we saw that:

-The more the grounding resistance of the electric pole is, the higher the current passes through grounding system of substation.

-The smaller the grounding wire is, the higher the current passes through grounding system of substation.

-We can clearly determine the lightning position that creates a risk to substation.

Table T3: Current (%) passing through grounding system of substation 1 in terms of lightning position k



Lightning position	%I (ПС-25)	%I (ПС-35)	%I (ПС-50)	%I (ПС-70)	%I (ПС-95)
0	78.7668	74.9228	71.8485	66.1107	64.1047
1	45.2183	46.8990	47.5679	47.5563	47.2339
2	25.9589	29.3571	31.4927	34.2093	34.8031
3	14.9025	18.3765	20.8500	24.6082	25.6437
4	8.5552	11.5030	13.8039	17.7018	18.8949
5	4.9113	7.2005	9.1390	12.7337	13.9222
6	2.8195	4.5072	6.0505	9.1599	10.2582
7	1.6186	2.8214	4.0058	6.5891	7.5585
8	0.9292	1.7661	2.6521	4.7398	5.5693
9	0.5334	1.1055	1.7558	3.4096	4.1036

Fig.12: (%) of current at grounding system of substation in terms of lightning position k

Table T4: (%) of current at grounding system of substation in terms of lightning position k

Lightning Potion	(%I) (ПС-35)	(%I) (ПС-50)	(%I) (ПС-70)	(%I) (ПС-95)
0	-3.8440	-6.9183	-12.6561	-14.6621
1	1.6806	2.3495	2.3379	2.0155
2	3.3982	5.5338	8.2504	8.8442
3	3.4740	5.9475	9.7058	10.7413
4	2.9478	5.2487	9.1466	10.3398
5	2.2891	4.2276	7.8223	9.0109
6	1.6877	3.2310	6.3404	7.4387
7	1.2027	2.3872	4.9705	5.9399
8	0.8369	1.7229	3.8106	4.6401
9	0.5721	1.2224	2.8761	3.5702

In general, when surveying a dangerous zone for substation, we obtained that, this dangerous zone only lies in first some spans of transmission line and the designers have to pay attention to it while designing transmission lines.

From Fig.12 (and from Table T4), We received, the bigger the values of current passing grounding system of substation are, the larger the grounding wire is.

3. Current passing the grounding system of substation with impact of R_1:

Surveying the following parameters:Changing grounding resistance of substation 1 from 0.1 to 1(Ω).
Resistance of grounding wire ПС-25: $R_s = 6.32(\Omega/km)$.
Grounding resistance of electric pole: $R_p = 5(\Omega)$.
Number of span: n=50.

Results received as follows:

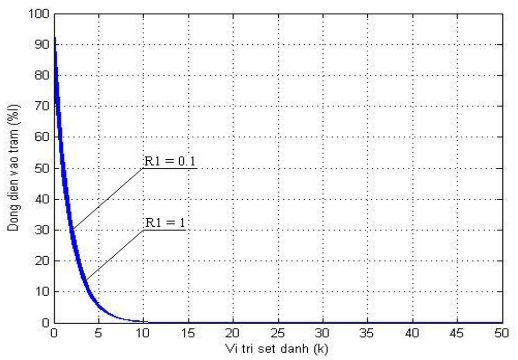


Fig.13: Graph of Current (%) passing the grounding system of substation 1in term of lightning position k

Table T5: (%) of current decrease at grounding system of substation in terms of lightning position k

Lightning Position	%I (R_1=0.1)	%I (R_1=0.2)	%I (R_1=0.3)	%I (R_1=0.4)	%I (R_1=0.5)
0	97.3751	94.8844	92.5180	90.2667	88.1224
1	55.9010	54.4711	53.1126	51.8202	50.5892
2	32.0916	31.2707	30.4908	29.7489	29.0422
3	18.4231	17.9519	17.5041	17.0782	16.6725
4	10.5763	10.3058	10.0487	9.8042	9.5713
5	6.0716	5.9163	5.7688	5.6284	5.4947
6	3.4856	3.3964	3.3117	3.2311	3.1544
7	2.0010	1.9498	1.9012	1.8549	1.8109
8	1.1487	1.1194	1.0914	1.0649	1.0396
9	0.6595	0.6426	0.6266	0.6113	0.5968

Lightning Position	%I (R_1=0.6)	%I (R_1=0.7)	%I (R_1=0.8)	%I (R_1=0.9)	%I (R_1=1)
0	86.0776	84.1256	82.2601	80.4756	78.7668
1	49.4153	48.2947	47.2238	46.1993	45.2183
2	28.3683	27.7250	27.1102	26.5220	25.9589
3	16.2856	15.9163	15.5634	15.2257	14.9025
4	9.3492	9.1372	8.9346	8.7408	8.5552
5	5.3672	5.2455	5.1292	5.0179	4.9113
6	3.0812	3.0113	2.9445	2.8807	2.8195
7	1.7688	1.7287	1.6904	1.6537	1.6186
8	1.0155	0.9924	0.9704	0.9494	0.9292
9	0.5830	0.5697	0.5571	0.5450	0.5334

From Fig.13 (and from Table T5) we saw that:

The smaller the grounding resistance of substation is, the larger the value of current passing grounding system of substation is. However, this change is not large and, thus, in this case, the dangerous zone can be considered to be unchanged.

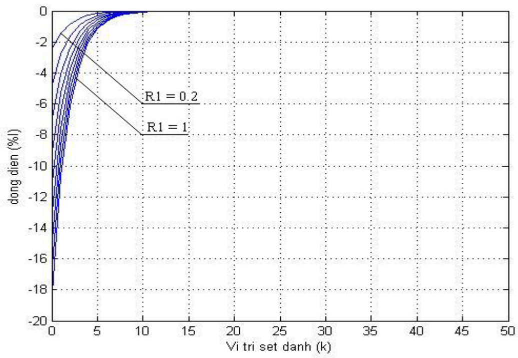


Fig.14: (%) of current at grounding system of substation in terms of lightning position k

Surveying the current decrease at grounding system of substation (see Fig.14), we obtained: the faster the current decreases, the smaller the grounding resistance of substation is.

3. CONCLUSIONS

This paper presents some formulas to calculate current passing through grounding system of high voltage substation and determines a dangerous zone of high voltage substation when lightning strikes at any point on the grounding wire of transmission line. It provides designers with information to design transmission lines properly.

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APPENDIX

To determine the equivalent impedance in case of the end of the grounding wire line connecting with a grounding system impedance (Z_1), we turn n pi-elements equivalent circuit into the n T-elements equivalent circuit and use characteristic matrix method.

If we consider elementary parameters of each span to be equal, then each T-circuit will be considered as a two-terminals network having the same characteristic matrix, as follows:

$$A_1 = A_2 = \ldots = A_n = A = \begin{bmatrix} \dfrac{2Z_p + Z_s}{2Z_p} & \dfrac{4Z_s Z_p + Z_s^2}{4Z_p} \\ \dfrac{1}{Z_p} & \dfrac{2Z_p + Z_s}{2Z_p} \end{bmatrix}$$

If we transform n series two-terminals networks into one then this equivalent two-terminals network will have the characteristic matrix as follows:

$$A_{TD} = A_1 \times A_2 \times \ldots \times A_n = A^n \qquad \text{(A. 1)}$$

Appling the Caylay-Hamilton theorem to solve (A .1), we have:

$$\Rightarrow A_{TD} = \begin{bmatrix} \beta_0 + \beta_1 A(11) & A(12) \\ A(21) & \beta_0 + \beta_1 A(22) \end{bmatrix} \qquad \text{(A. 2)}$$

where

$$\begin{cases} \beta_0 = \dfrac{\lambda_2 \lambda_1^n - \lambda_1 \lambda_2^n}{\lambda_2 - \lambda_1} \\ \beta_1 = \dfrac{\lambda_1^n - \lambda_2^n}{\lambda_1 - \lambda_2} \end{cases}$$

and

$$\begin{cases} \lambda_1 = \dfrac{2Z_p + Z_s + \sqrt{4Z_s Z_p + Z_s^2}}{2Z_p} \\ \lambda_2 = \dfrac{2Z_p + Z_s - \sqrt{4Z_s Z_p + Z_s^2}}{2Z_p} \end{cases}$$

The two-terminals network with the characteristic matrix determined at (A.2) is transformed inversely into T-elements equivalent circuit as in Fig .A.1

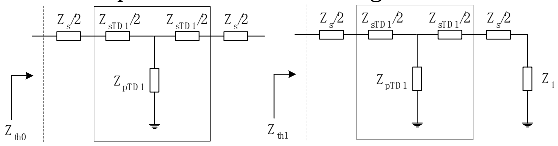

Fig .A.1 Equivalent Thevenin circuit

where parameters of T-elements equivalent circuit as follows:

$$\begin{cases} Z_{sTD}/2 = Z_p + \dfrac{Z_s}{2} + Z_p \dfrac{\beta_0}{\beta_1} - \dfrac{Z_p}{\beta_1} \\ Z_{pTD} = \dfrac{Z_p}{\beta_1} \end{cases}$$

Thus, the Thevenin impedance "seeing" from the position that lightning strikes to the end of the grounding wire line in case of open-ended grounding wire or the end of the grounding wire connecting with the grounding system impedance of substation (Z_1):

$$\begin{cases} Z_{th0} = Z_s + Z_p \left(1 + \dfrac{\beta_0}{\beta_1}\right) \\ Z_{th1} = Z_{th0} - \dfrac{Z_{pTD}^2}{Z_{th0} + Z_1} \end{cases} \qquad \text{(A. 3)}$$

where:

$$Z_{pTD} = \frac{2^n Z_p^n \sqrt{4Z_s Z_p + Z_s^2}}{\left(b + \sqrt{4Z_s Z_p + Z_s^2}\right)^n - \left(b - \sqrt{4Z_s Z_p + Z_s^2}\right)^n}$$

and

$b = 2Z_p + Z_s$.

BIOGRAPHY

Chuong Ho Van Nhat was born in 1954, Hue Province, VietNam. He received Bechelor of Science degree in Electrical Engineering from Ho Chi Minh City University of Technology in 1977 and Philosophy Doctor degree in High Voltage Engineering from Kiev Polytechnique University, Ucraine in 1997. Now, he has been as senior lecturer of Power Systems Department of HCMCity University of Technology. His main research interests concentrate in the field of Grounding System, Overvoltages in Power Systems and Measurements on High Voltage.